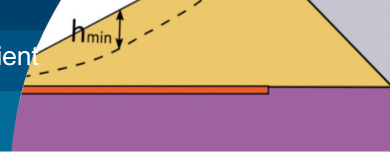

The impact of considering the vertical seismic coefficient k_v on the pseudo-static slope stability analysis of downstream tailings sand dams

El impacto de incluir el coeficiente sísmico vertical k_v en el análisis de estabilidad pseudo-estático de tranques de relaves construidos con arenas mediante el método constructivo aguas abajo

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In Chile, the limit equilibrium analysis under pseudo-static conditions is compulsory according to the Supreme Decree 248 (DS248, 2007), which establishes a minimum factor of safety (FoS) of 1.2 for stability analysis. In Chilean geotechnical practice, it is usually considered just the horizontal seismic coefficient (k_h) for the analyses. However, there is a constant discussion about the necessity of applying both horizontal and vertical seismic coefficient (k_v) into the analyses. In addition, there is uncertainty about what k_v/k_h should be considered and the effect that the sense of application (upward or downward) could have on the FoS. This paper presents an analysis of the effect of considering different $|k_v|/k_h$ from 0 to 1 on both analysis directions for generic downstream tailings sand dam. Based on this, different dam heights, beach lengths and seepage conditions are also analysed. The obtained results show that when both k_h and k_v are applied, the FoS increase if k_v acts downward and decrease when it acts upward. In addition, the effect for $|k_v|/k_h \leq 0.5$ is almost neglectable, especially for $k_h \leq 0.15$. Furthermore, although a short beach length significantly impacts the FoS, the influence of applying both k_h and k_v seems to be independent of the beach length.

Keywords: pseudo-static analysis, downstream tailings dams, vertical seismic coefficient

En Chile, de acuerdo con el Decreto Supremo 248 (DS248, 2007), el análisis de equilibrio límite en condiciones pseudo-estáticas es obligatorio, debiendo asegurarse un factor de seguridad mínimo (FS) de 1.2. En la práctica geotécnica chilena, generalmente en los análisis se considera solo el coeficiente sísmico horizontal (k_h). Sin embargo, existe una constante discusión sobre la necesidad de también aplicar el coeficiente sísmico vertical (k_v) en los análisis. Además, existe incertidumbre sobre qué razón de k_v/k_h se debe considerar para los análisis y el efecto en los factores de seguridad con el sentido de aplicación del coeficiente sísmico vertical (hacia arriba o hacia abajo). Este artículo presenta un análisis del efecto de considerar razones de k_v/k_h de 0 a 1 en ambas direcciones de análisis para un tranque de relaves genérico con muro de arena, construido mediante el método de aguas abajo para diferentes alturas del muro, longitudes de playa y condiciones de drenaje. Los resultados obtenidos indican que cuando se aplican tanto k_h como k_v, el FS aumenta si k_v actúa hacia abajo y disminuye si actúa hacia arriba. Además, para $|k_v|/k_h \leq 0.5$ el efecto es prácticamente despreciable, especialmente para $k_h \leq 0.15$. Por último, si bien un largo de playa menor tiene un gran impacto en el FS, la aplicación de k_h y de k_v parece ser independiente del largo de playa.

Palabras clave: análisis pseudo-estático, tranques de relaves, coeficiente sísmico vertical

Introduction

Several tailings storage facilities (TSFs) failures have been reported worldwide in the past decades (Rico *et al.*, 2008). Most of them occurred in tailings dams that were constructed using cyclone sand tailings (the coarse fraction of the tailings) as the primary material of the dam (Villavicencio *et al.*, 2014). In recent years, great attention has had the dam disasters in Canada on the Mount Polley Dam (2014) and the failures of the Brazilian dams in the

Fundão dam in 2015 and more recently in the Feijão I dam in 2019. All of them causing severe environmental damages (Morgenstern *et al.*, 2015, 2016; Robertson *et al.*, 2019).

In Chile, most of the tailings dam's failures have been triggered by earthquakes (mainly because of flow failure or seismic liquefaction), although also many failures have been recorded due to overtopping, seepage, and foundation instability (ICOLD, 2001; Troncoso, 2002; Rico *et al.*, 2008; Ramírez, 2010; Villavicencio *et al.*, 2014).

In terms of the Chilean regulatory framework, two major regulations have been published in the mining history of Chile regarding the design, construction, and operation of tailings storage deposits (Villavicencio *et al.*, 2014). These are the Supreme Decree No. 86 (DS86, 1970) and the Supreme Decree No. 248 (DS248, 2007). The first one was influenced by the collapse of the sand tailings dam of El Cobre after the M_w = 7.4 La Ligua 1965 earthquake. This Supreme Decree (DS86, 1970) established the first guidelines for tailings dam design forbidding the construction of upstream dams and demanding a minimum factor of safety FoS of 1.2 under pseudo-static conditions, among other guidelines (Barrera *et al.*, 2011).

Supreme Decree DS248 (2007) updated Supreme Decree DS86 (1970) on the 11 of April 2007. According to Villavicencio *et al.* (2014), there are some of the new geotechnical requirements: sand tailings for dam construction must have less than 20% of fines content (< 0.075 mm), a minimum freeboard and a crest width of 2 and 1 m must be ensured, respectively. In addition, the retaining sand dam must have an underlying drainage system, and the pond must be located as far as possible from the sand dam. Regarding the slope stability of tailings dams, limit equilibrium analyses (LEA) are required for the operational and closure phases, considering static and pseudo-static conditions with ensuring a minimum FoS of 1.2. Moreover, it establishes that is required a dynamic stress-strain numerical analysis to assess horizontal and vertical displacements for tailings dams over 15 m height, which are usually defined as large dams (ANCOLD, 2012).

Although performing pseudo-static slope stability analysis is compulsory before carrying out the dynamic analysis, and it can even cause a project to be discarded if the FoS is less than 1.2, no guidelines are provided regarding the consideration of the vertical seismic coefficient k_v into the analyses. Moreover, when k_v is considered, the discussion usually arises about what vertical to the horizontal seismic coefficient ratio k_v/k_h and direction of application (upward or downward) should be considered for the analyses. In this paper, a number of combinations of k_v/k_h from 0 to 1.0 are analysed considering both analysis directions. The analysis is performed using a deterministic approach for a generic downstream tailings sand dam for different dam heights, beach lengths and seepage conditions to quantify the effect on the FoS when considering the k_v under all these conditions.

Effect of k_v on seismic slope stability

Kramer (1996) defined the evaluation of seismic slope stability as one of the most frequent and challenging activities of geotechnical earthquake engineering practice. Analytical methods ranging from pseudo-static limit equilibrium analysis are widely incorporated in several commercial software that can rapidly compute and assess the slope performance providing a FoS with different computing methods. In general terms, the pseudo-static approach is essentially the same as the static one, but it considers a horizontal force F_h that represents the earthquake load (Vick, 1983). This force is usually represented by the horizontal seismic coefficient k_h multiplied by the weight of the potential sliding mass W. Figure 1 presents the typical setting of a generalised pseudo-static analysis where both horizontal and vertical forces F_v are considered.

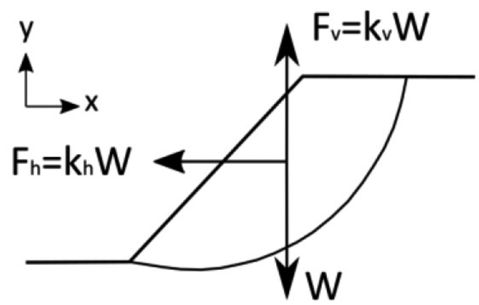

Figure 1: Pseudo-static analysis approach (Melo and Sharma, 2004)

Overall, in low seismicity countries, k_h tends to be lower than 0.1, while in highly seismic countries such as Chile, Peru, Mexico, and Japan, this value ranges from 0.1 to

0.25 depending on the area and the structure type (Melo and Sharma, 2004; Towhata, 2008; Campaña, 2019). In the geotechnical practice of tailings dams, the k_h value is still obtained as a function of the peak ground acceleration PGA of the site-specific probabilistic or deterministic hazard assessment (Kramer, 1996; Towhata, 2008; Campaña, 2019). In the case of Chile, it is widely used the expression proposed by Saragoni (1993), which was adopted from Noda and Uwabe (1976) and modified for Chilean subduction earthquakes for quay wall applications. This expression is presented in the following expression (1):

$$k_h = 0.3(\text{PGA}) \quad \text{if PGA} < 0.66\text{g}$$
$$k_h = 0.22(\text{PGA})^{1/3} \quad \text{if PGA} \geq 0.66\text{g} \qquad (1)$$

Regarding k_v, there is no unanimity on an expression to assess its value, and it is usually not included in the regulatory frameworks and hence neglected in the analysis (k_v = 0). Nonetheless, when is considered, it is usually estimated as a fraction of the horizontal seismic coefficient ranging from 30 to 100% of k_h. This consideration arises, given historical data that shows that the up-down component of earthquakes varies between those values of the horizontal components (EW-NS) (Towhata, 2008). Hence, both k_h and k_v end up being commonly estimated from the PGA. Consequently, with the increasing values of PGA that are currently being reported in Chilean earthquake engineering practice in both probabilistic and deterministic site hazard assessments, it is important to quantify the influence of the k_v parameter into the pseudo-static analyses.

Historically, there are different views about how the results can be affected. For instance, Sarma (1975) found that vertical pseudo-static forces were not important enough to be considered in the design of earth dams. On the other hand, authors have recently found that the effect varies whether the slope has cohesion or is purely frictional. Sahoo *et al.* (2018) found that the FoS and yield acceleration of a cohesionless soil slope increases with an increase in k_v for a given value of k_h when k_v is applied in the downward direction, and the effect is the opposite when k_v is applied upward. Sahoo *et al.* (2018) also found that the effect of k_v on the slope stability is neglectable when k_h < 0.2 and that the effect of k_v is significant when $k_h \geq 0.2$.

Regarding materials with both cohesive and frictional components (c-ϕ' slope), Sahoo and Shukla (2021) found that the application of k_v in the upward direction results in a lower FoS. However, Shukha and Baker (2008) found that for very steep c-ϕ' slopes, the critical condition is when k_v is applied in the upward direction and for a gentle slope, this occurs when k_v is applied in the downward direction. Specifically, if k_v is neglected, significant errors could be produced when computing the FoS for steep (> 45°) and gentle slopes, while for intermediate slopes, the error is tolerable (Shukha and Baker, 2008). Another key finding of that study is that the error increases with the increase of the $|k_v|/k_h$ ratio, being critical for places close to the epicentre, where $|k_v|/k_h$ is close to 1 (Shukha and Baker, 2008).

Geotechnical model

Figure 2 shows the generic model developed used for the stability analysis of a downstream construction dam. Based on this, four geotechnical units can be identified: the foundation soil, basal drain, tailings sand dam and tailings slimes. For simplification, the started dam, usually constructed with borrow material or rockfill (Vick, 1983; Blight, 2010), was not considered.

A crest width of 10 m was considered with a freeboard of 3 m. Regarding the dam height, five dam heights H were analysed: 20, 40, 60, 80 and 100 m for two different overall downstream slope inclinations i: 4:1 and 3.5:1 (H:V), which results in a slope angle α of 18° and 16°, respectively. An average slope of 2.5:1 (H:V) was considered constant for all the analyses for the upstream slope. In addition, a slope of 1% was considered on the tailings surface as an average condition for conventional tailings (Blight, 2010). For all the mentioned cases, three beach lengths ratios L/H were analysed: 5, 7 and 9, and two drainage conditions were also considered, the first one with a fully operational drain, i.e. zero pressure boundary condition (BC) applied, and a

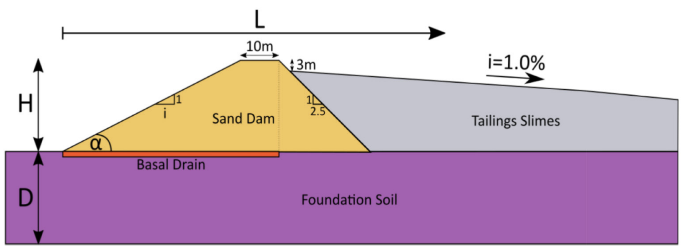

Figure 2: Tailing dam geotechnical model

clogged drained scenario (no zero-pressure BC applied). All these combinations of cases were analysed for a k_h = 0.1, 0.15, 0.2 and 0.25 considering $|k_v|/k_h$ = 0, ⅓, ½, ⅔ and 1 and k_v applied in the upward (↑) and downward (↓) direction. Figure 3 summarises all the combinations analysed, which resulted in 2160 cases of analysis.

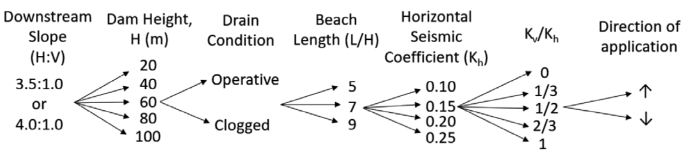

Figure 3: Example of the decision tree considered for the analysis

For estimating the phreatic surface for the different beach lengths ratios *L/H*, a finite element steady-state analysis was performed in Slide2 (2018) for each slope stability analysis. Regarding the hydraulic properties of tailings sands and slimes, a saturated constant permeability of K_v^{sat} = $3 \cdot 10^{-6}$ m/s and K_v^{sat} = 10^{-7} m/s was considered according to Valenzuela (2015, 2016). Regarding the anisotropy, an increase of 5 and 10 times in the horizontal direction has been considered for the tailings sands and slimes, respectively. These values follow similar procedures available in the literature for steady-state analyses, such as Valenzuela (2015, 2016) and Sarsby (2013). Regarding the drainage system, a saturated constant permeability of K_v^{sat} = 10^{-4} m/s (for both directions) has been considered for the basal drain (Blight, 2010). For simplicity, the foundation soil has been considered impermeable ($K_v^{sat} = 10^{-20}$ m/s).

In terms of the mechanical properties, it is assumed a drained behaviour for the tailings sands under the assumption that tailings sands have been compacted to 95% of the modified Proctor test and that the stress levels will not cause a contractive behaviour of the material. Notwithstanding, this assumption is not the standard practice and is far from the Chilean engineering practice; in the second part of this research, the undrained response (purely cohesive materials below the phreatic surface) is considered in the analyses to compare both results.

Table 1 presents the Mohr-Coulomb parameters adopted for each unit. Again, to isolate the effect of the foundation and the basal drain, both materials were considered with infinite strength. In general terms, tailings slimes and sands were considered cohesionless according to Blight (2010) and Sarsby (2013). The friction angle of tailings sands and slimes was considered using the average parameters provided by Vick (1983).

Figure 4 shows the potential slipping surfaces considered for the FoS estimation. In terms of the potential slipping surface shape, only non-linear semicircular-type and wedge-type shapes were considered to estimate the FoS, following recommendations of the literature (Villavicencio *et al.*, 2014, Troncoso, 1996; Blight, 2010). Regarding the potential slipping volume, only slipping surfaces that involves at least 50% of the crest width were considered. In addition, only potential slipping surfaces with a minimum depth h_{min} of 20% of the dam height *H* were considered for the FoS computation. Finally, the FoS was estimated using the Morgenstern and Price (1965) methodology implemented into Slide2 (2018), which consider the equilibrium of forces (x-y) and moments.

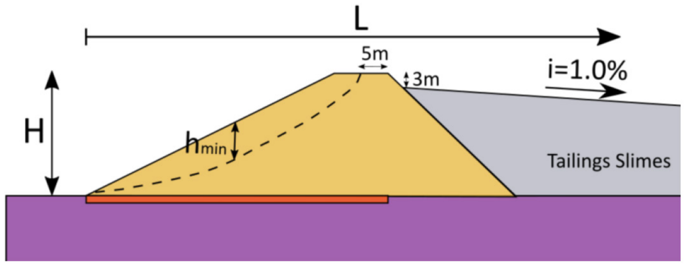

Figure 4: Slip surface shape considered for the analyses

Table 1: Geotechnical properties considered for the analyses

Geotechnical unit	Dry unit weight γ_d, kN/m³	Saturated unit weight γ_{sat}, kN/m³	Friction angle ϕ, °	Cohesion *c*, kPa	Saturated vertical permeability K_v^{sat}, m/s	Saturated horizontal permeability K_h^{sat}, m/s
Sand dam	16	18	35	0	3×10^{-6}	1.5×10^{-5}
Tailings	14	18	25	0	10^{-7}	10^{-6}

Results

Figure 5 shows the FoS obtained for the slipping surfaces for a 100 m dam height, H:V = 3.5:1.0 slope, considering a clogged drain, a beach length of *L/H* = 5, and seismic coefficients of k_h = 0.2 and k_v = -0.2. In addition, Figure 6 shows the results obtained for a downstream slope of H:V = 4:1 and *L/H* = 5 for two different pseudo-static scenarios k_h = 0.1 and 0.25. According to this, Figure 6(a) presents the results for a fully operative drain (zero pressure BC applied) and Figure 6(b) shows the results for a clogged drain scenario. From Figure 6(a), the results suggest that the dam's height has almost no effect on the FoS when the drain is connected to the atmospheric pressure. In addition, it seems that an increase of the $|k_v|/k_h$ causes the same effect for each dam height of analysis. This effect can be explained since, if the drain has the zero-pore pressure BC applied, all the water is collected on the basal drain, and no water table appears on the toe of the dam. Hence, the potential slipping surface is always "dry", and the pore water pressure does not influence the potential sliding surface. On the other hand, from Figure 6(b), there is a confirmation that the phreatic surface influences the results by decreasing the FoS.

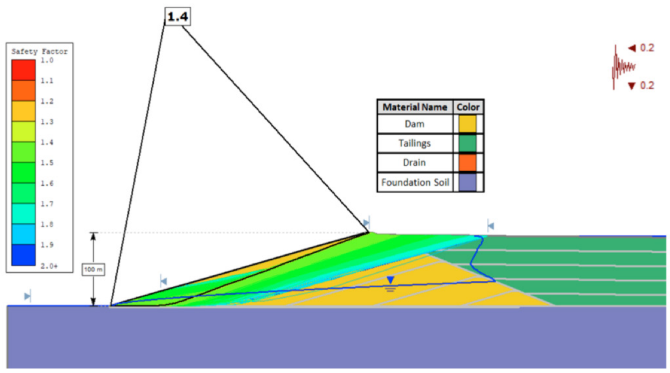

Figure 5: Example of the slipping surfaces obtained for a downstream dam with a H:V = 3.5:1.0 slope; H = 100 m, a beach length of L/H = 5, clogged drain, k_h = 0.2 and k_v = -0.2

From Figure 6, when there is a water table acting on the toe of the dam, an increase in the dam's height decreases the FoS. Moreover, from both Figures 6(a) and 6(b), the application of k_v in the downward direction increases the FoS, while when k_v is applied in the upward direction, the FoS decreases, which is consistent with the results reported in the literature. Furthermore, the results presented in

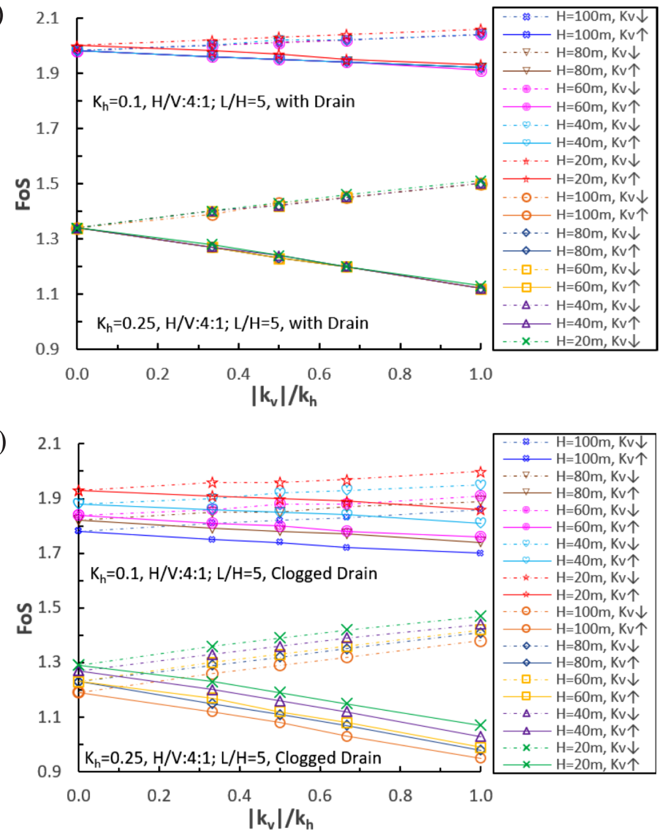

Figure 6: FoS for different $|k_v|/k_h$ ratios for L/H = 5 and H:V = 4:1 for: (a) fully operative drain and (b) clogged drain

Figure 6 suggests that the change on the FoS varies with a slightly higher rate when $|k_v|/k_h$ is bigger than 0.5.

The results indicate that a higher k_h causes an increase in that rate, decreasing the FoS significantly for $|k_v|/k_h >$ 0.5. According to this, Figure 7 presents the percentage of change on the FoS for a dam height of 100 m and *L/H* = 5 considering an (a) operative drain and (b) a clogged drain. Based on this, when $|k_v|/k_h \leq 0.5$, the change on the FoS is within a range of ±5% (depending on the direction of application of k_v). However, when $|k_v|/k_h > 0.5$, the increase or decrease on the FoS is significant for $k_h \geq 0.2$, moderated for k_h = 0.15 and very low for k_h = 0.10 (less than 5%). In addition, when k_v is applied upward, it has a slightly more substantial influence on the FoS than a k_v applied in the downward direction.

Regarding the effect of the inclination of the downstream slope, Figure 8(a) presents the results of the FoS obtained for an H:V = 3.5:1 for the same analysis conditions as in Figure 6(b). In addition, Figure 8(b) compares the percentage of change on the FoS for H:V = 4:1 and 3.5:1.

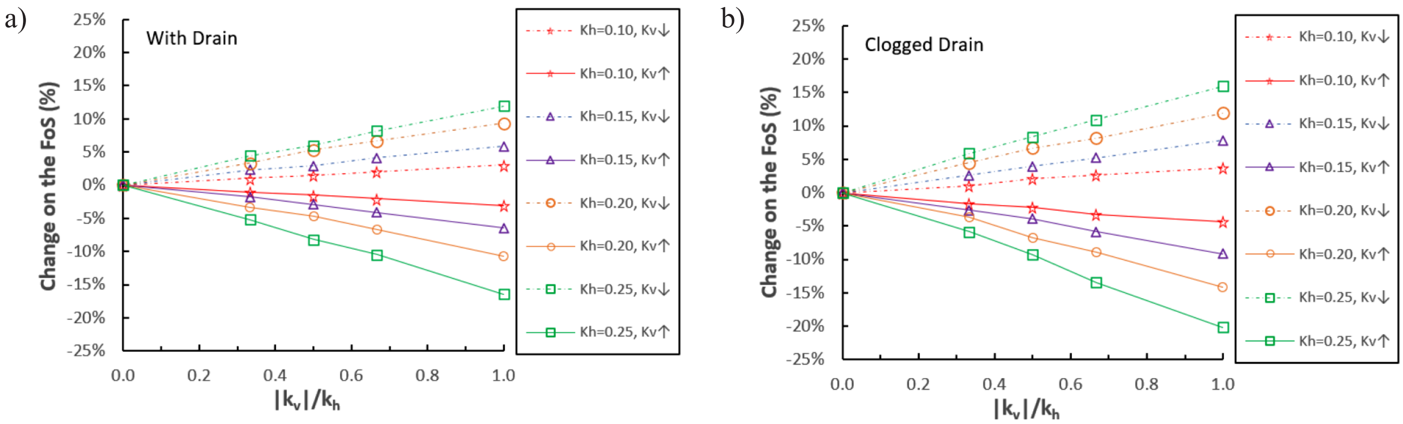

Figure 7: Percentage of change for different k_h and $|k_v|/k_h$ considering an: (a) operative drain and (b) clogged drain

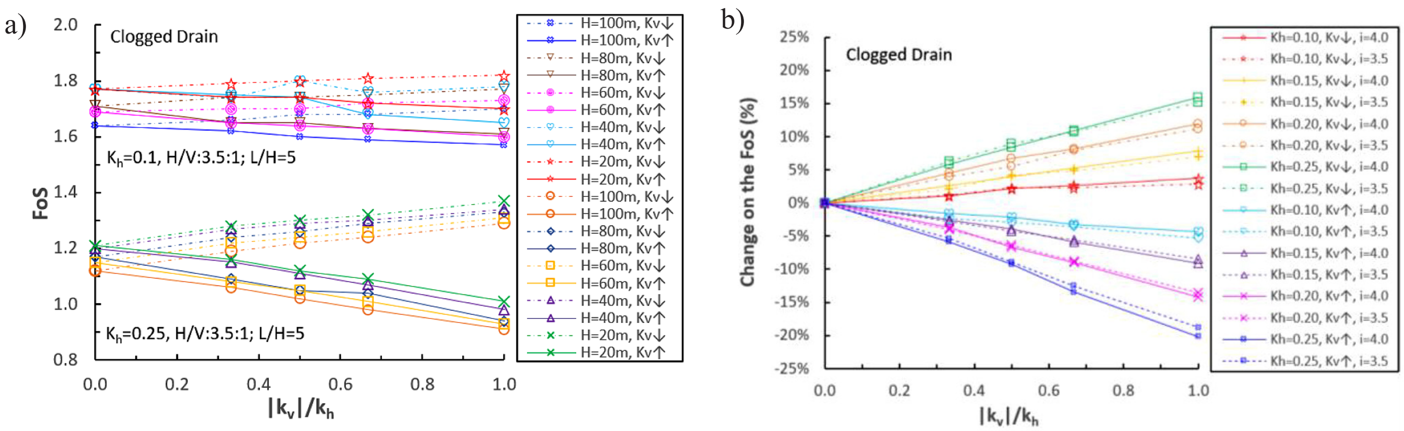

Figure 8: (a) FoS obtained for H:V = 3.5 and k_h = 0.1 and 0.25 and (b) comparison between the percentage of change on the FoS for both downstream slopes

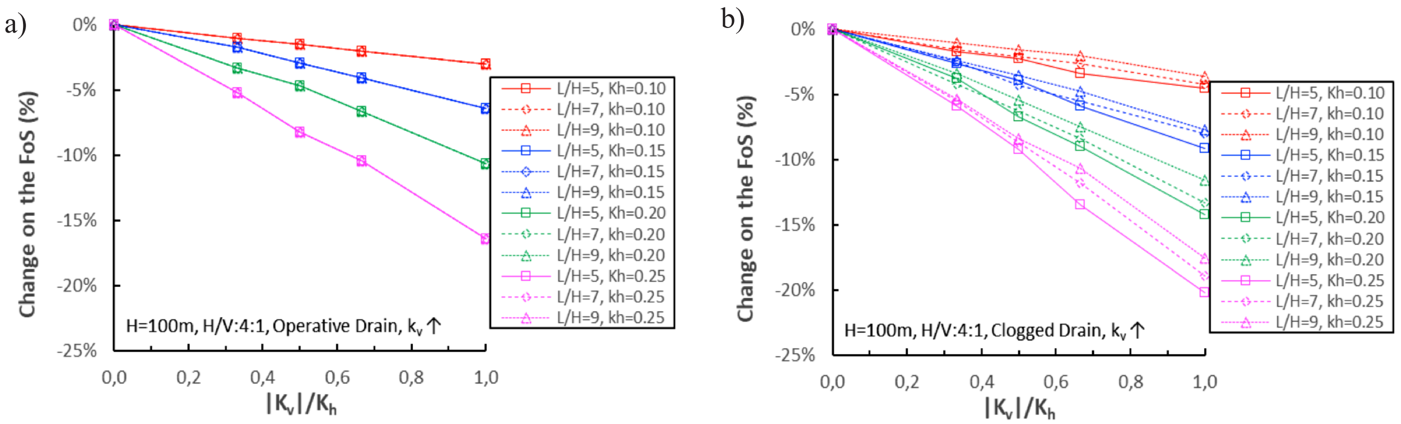

Figure 9: Percentage of change on the FoS for different $|k_v|/k_h$ ratios for H = 100 m and H:V = 4:1 for: (a) fully operative drain and (b) clogged drain

From both figures, the effect of a slightly steeper slope seems to decrease the effect of increasing both k_h and k_v. Figure 8(b) shows that the percentage of change on the FoS is slightly higher on the H: V = 4:1 slope. These results validate the results obtained by Shukha and Baker (2008).

Finally, Figure 9 shows the effect of the beach length on the FoS and how the FoS is influenced by k_v. These results show that the beach length *L/H* is one of the most influencing factors on the FoS. However, as reported previously, the effect on the FoS is only significant when

$k_h \geq 0.15$ and $|k_v|/k_h \geq 0.5$, where the decreasing rate of FoS increases.

Conclusions

A comprehensive analysis of a downstream tailings dam subjected to the combined effect of vertical and horizontal pseudo-static forces was conducted for different conditions of phreatic surfaces, downstream slopes, and dam heights. The main conclusions of this study are summarised as follows:

- Similar to the results presented by Sahoo *et al.* (2018), for cohesionless materials (ϕ' ≠ 0, *c*'= 0), the FoS increase when k_v acts in the downward direction, while there is a decrease in the FoS when k_v acts upward. In addition, this effect is slightly more significant for gentle slopes. Specifically, the results show that H:V = 4:1 slopes experience a higher reduction or increase on the FoS (depending on the sense of application on the k_v) for a similar $|k_v|/k_h$ regardless of the k_h value when the results are compared for those obtained on H:V = 3.5:1 model.
- When a fully operative drain is considered (*i.e.*, when their pores are connected to the atmospheric pressure), a lower effect of both k_h and k_v can be expected because the basal drain collects all the water from the pond and minimises the water within the dam, reducing the hydrodynamic pressures. Furthermore, the phreatic surface does not reach the potential slipping surface. Hence, pore water pressure does not influence the analysis. In addition, when the drain is operative, the studied beach lengths, *L/H* = 5, 7 and 9, do not affect the FoS for all the dam heights.
- Similar to the results obtained by Sahoo *et al.* (2018), when the drain is considered with the zero-pressure boundary condition applied, the effect of $|k_v| = k_h$ on the slope stability is almost neglectable for $k_h = 0.10$ (±3%) and $k_h = 0.15$ (±6%), moderate for $k_h = 0.20$ (+9% and -11%), and significant for $k_h = 0.25$ (+12% and -16%). In general, when $|k_v|/k_h \leq 0.5$ is considered, the effect is lower than ±5% for $k_h \leq 0.20$ and lower than ±8% for $k_h = 0.25$.
- On the other hand, when the drain is clogged, the FoS change significantly when both k_h and k_v are applied. This consideration is one of the factors that most influence the FoS, regardless of the chosen values of k_h and $|k_v|/k_h$. Indeed, there is also a moderate influence of the dam height *H* for a clogged drain, where taller dams show a lower FoS but a similar percentage of change with an increasing $|k_v|/k_h$.
- If the basal drain is considered clogged, the effect of $|k_v| = k_h$ on the slope stability is relatively higher than the dry condition simulated by the fully operative drain. However, even considering $|k_v| = k_h$ the changes on the FoS are almost neglectable for $k_h = 0.10$ (±4%), but the influence could be considered moderate for $k_h = 0.15$ (+8% and -9%), significant for $k_h = 0.20$ (+12% and -14%), and very significant for $k_h = 0.25$ (+16% and -20%). In general, when $|k_v|/k_h \leq 0.5$ is considered in the analysis, the effect is lower than ±5% for $k_h \leq 0.15$ and lower than ±10% for $0.15 \leq k_h \leq 0.25$.
- In recent years performance-based design approaches have been introduced to estimate more realistic values of k_h based on finite element or finite difference numerical analyses (Bray and Travasarau, 2011; Bray *et al.*, 2018). These methods seem more realistic than estimating k_h from the PGA since they consider the dynamic soil response for different dam geometries, soil's shear strength and stiffness and seismic records. However, they are still recent, and geotechnical practitioners are still not familiar with them even though they seem reliable. In addition, these methods neglect the effect of the vertical seismic component.

Future work

This study considered a drained response of the sand dam and tailings below the phreatic surface. Thus only the effective shear strength was considered in the analyses. However, this is not the common standard in tailings engineering practice since materials below the phreatic surface usually develop pore water pressure under a seismic event. Therefore, the authors are currently performing pseudo-static limit equilibrium analyses considering an undrained behaviour below the phreatic surface and a drained response above the phreatic surface. Based on this, this study corresponds to the first step of a major study, where the idea is to compare both results to determine the different effects that k_v could have in the FoS. In addition, the authors are also performing *c*-ϕ' reduction stress-strain analysis under static and pseudo-static conditions to compare the effect of considering the construction stages on the field stress and the effect on the FoS.

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